The orbits of CEMP-s binaries and what we can learn from them

Onno Pols
Dept. of Astrophysics/IMAPP, Radboud Universiteit Nijmegen

with

Martha Saladino (PhD), Carlo Abate, Richard Stancliffe

carbon-enhanced metal-poor stars

- 6–25% of halo stars with [Fe/H] < −2 having [C/Fe] > 1
  Lucatello+2006, Lee+2013

- **CEMP-s** stars (~80%): also enhanced in heavy elements produced by the s-process
  ⇒ AGB nucleosynthesis

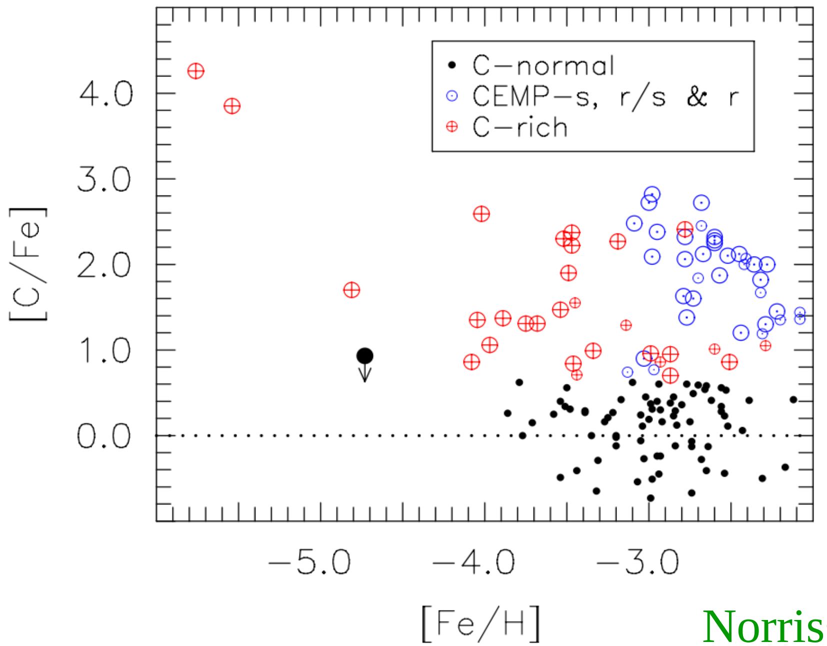
- some also appear r-process enriched: CEMP-r/s (or CEMP-i)

- probably all binaries
  Lucatello+2005, Starkenburg+2014, Hansen+2016

- **CEMP-no** stars: no heavy-element enhancements

- dominate at [Fe/H] < −3

- normal (field) binary properties
  Starkenburg+2014, Hansen+2015



Norris+2013

carbon-enhanced metal-poor stars

- 6–25% of halo stars with [Fe/H] < −2 having [C/Fe] > 1
  Lucatello+2006, Lee+2013

- **CEMP-s** stars (~80%): also enhanced in heavy elements produced by the s-process
  ⇒ AGB nucleosynthesis

- some also appear r-process enriched: CEMP-r/s (or CEMP-i)

- probably all binaries
  Lucatello+2005, Starkenburg+2014, Hansen+2016

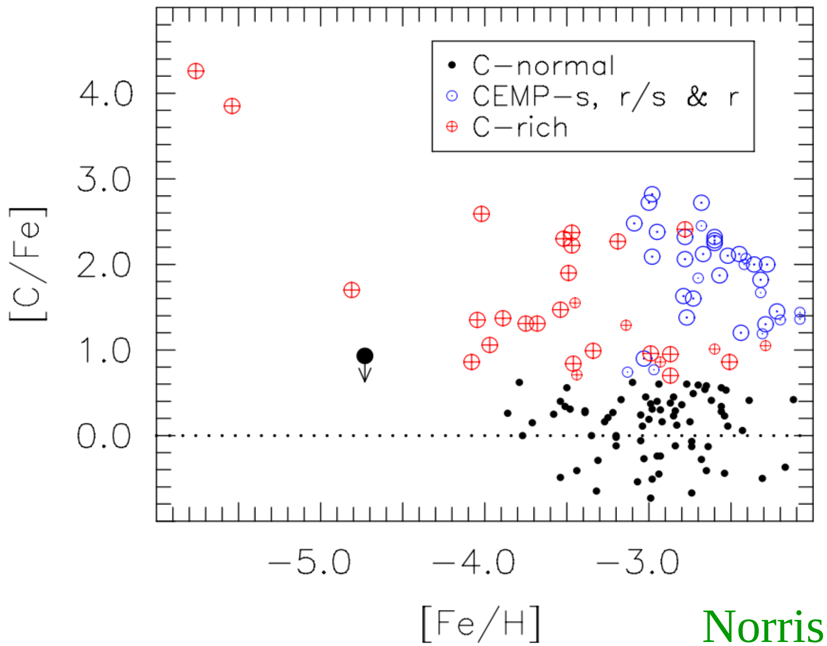
- likely origin in mass transfer from companion star during AGB phase (similar to Ba and CH stars)

- **CEMP-no** stars: no heavy-element enhancements

- dominate at [Fe/H] < −3

- normal (field) binary properties
  Starkenburg+2014, Hansen+2015

- probably entirely different origin



Norris+2013

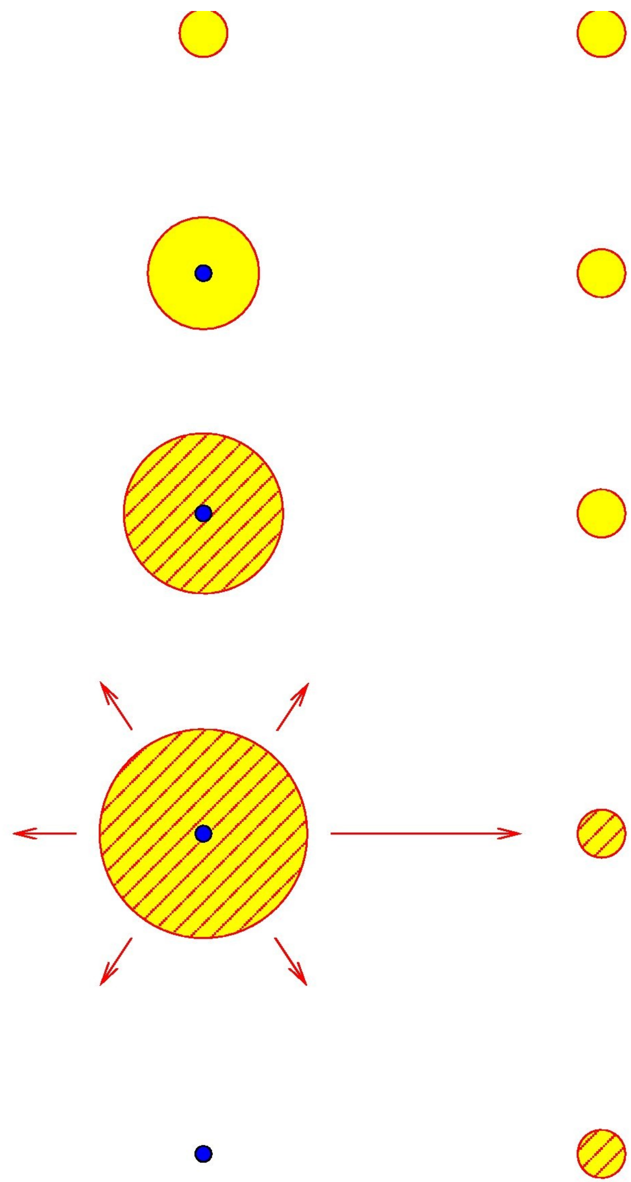
chemically polluted binaries

- binaries with an unevolved (MS, RG) star showing signs of AGB nucleosynthesis (carbon, s-process elements):

	Ba stars	**CH stars**	**CEMP-s stars**
- population:	Galactic disk		halo
- metallicity:	~0.5 Z_{sun}	~0.1 Z_{sun}	< 0.01 Z_{sun}
- fraction (RG):	~1%	~2%	6–20% (!)
- duplicity:	100%	100%	100% (?)

- probes of AGB nucleosynthesis at low metallicity
- probes of binary interaction processes at low/intermediate stellar mass

binary evolution scenario



MS ($M_1 > 1.5$ at $Z = Z_{sun}$
$M_1 > 0.9$ at $Z < 10^{-4}$)
Karakas 2010

MS ($M_2 < M_1$)

first giant branch

AGB: surface C ↑ s ↑

mass loss (wind, RLOF)

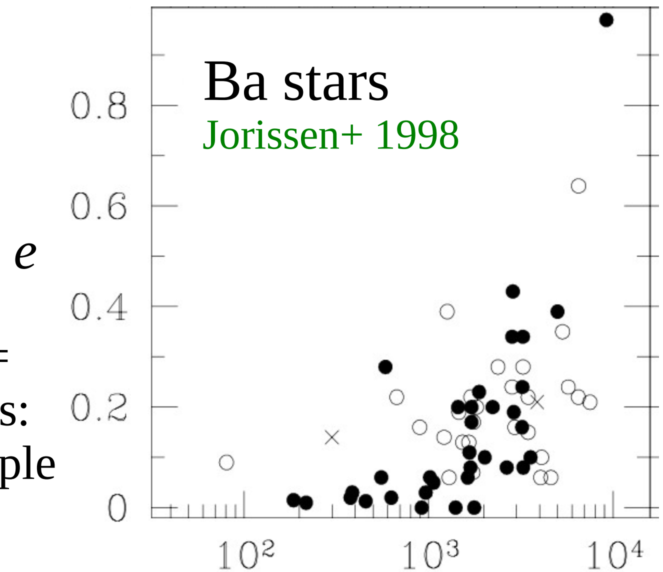
accretion: C ↑ s ↑

white dwarf

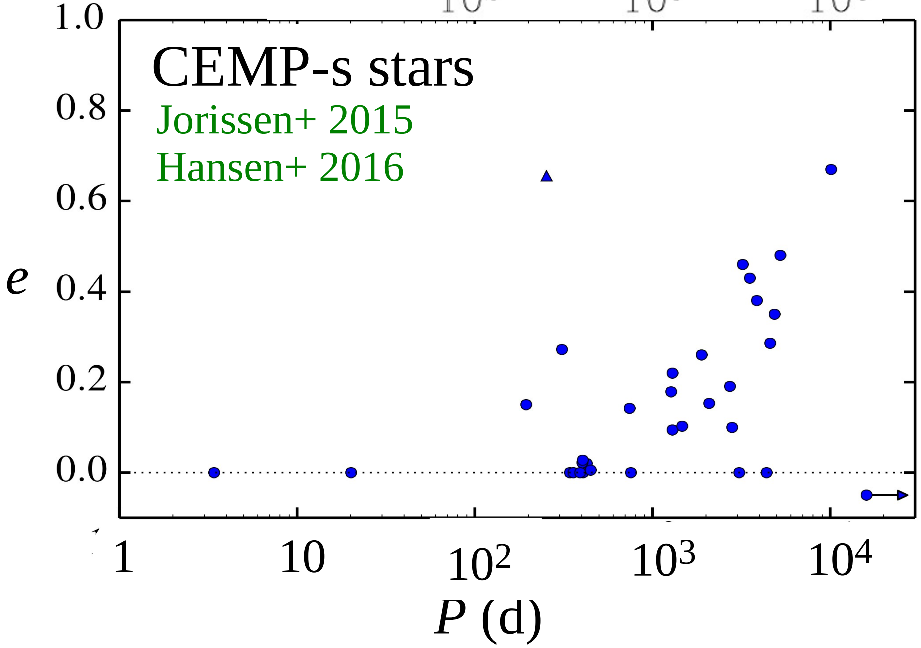
Ba star
CH star
CEMP-s star

orbits of polluted binaries

eccentricity versus orbital period



filled circles = strong Ba stars: complete sample

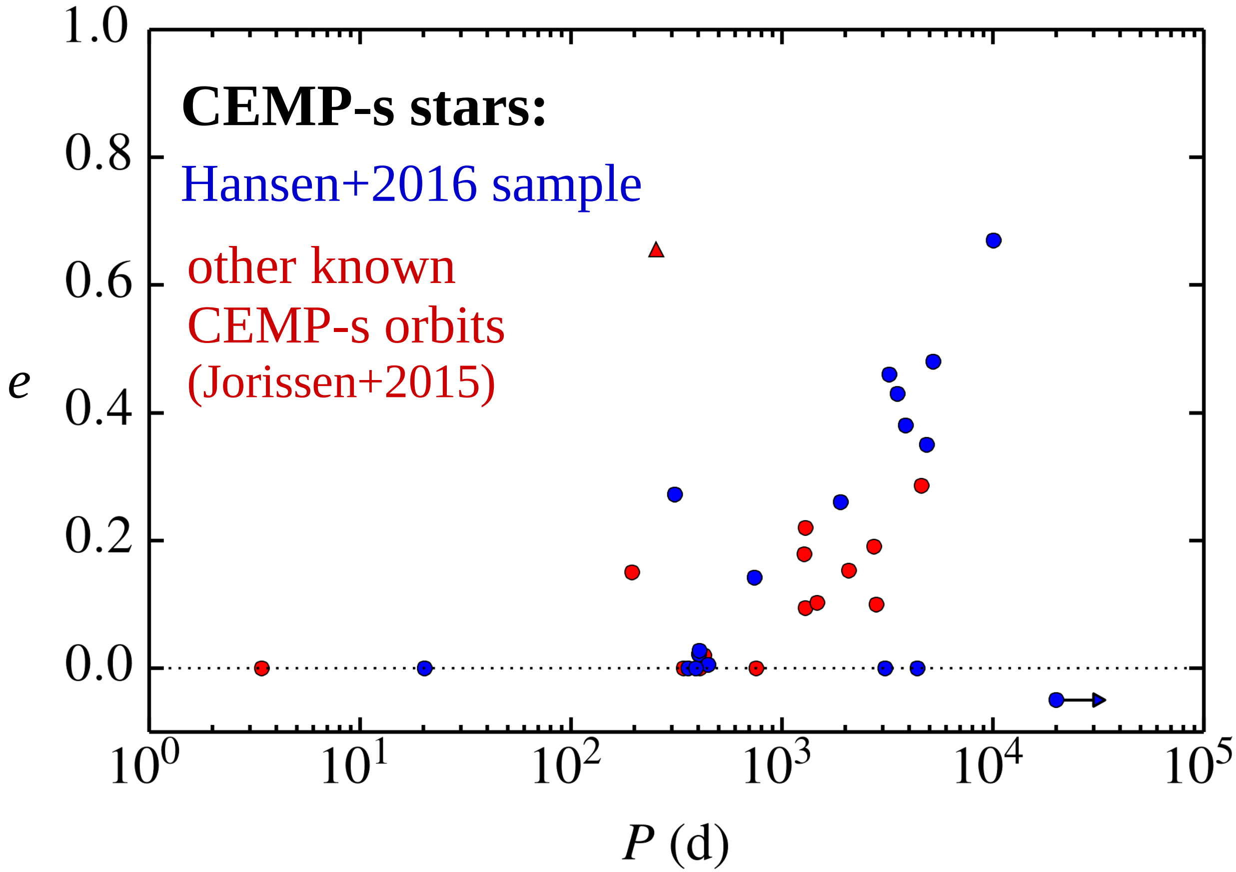


- periods mostly $10^2 - 10^4$ days
- substantially eccentric (but less so than unevolved binaries at same P)
- mass functions consistent with WD companions

orbits of polluted binaries

eccentricity versus orbital period

- periods mostly $10^2 - 10^4$ days
- substantially eccentric (but less so than unevolved binaries at same *P*)

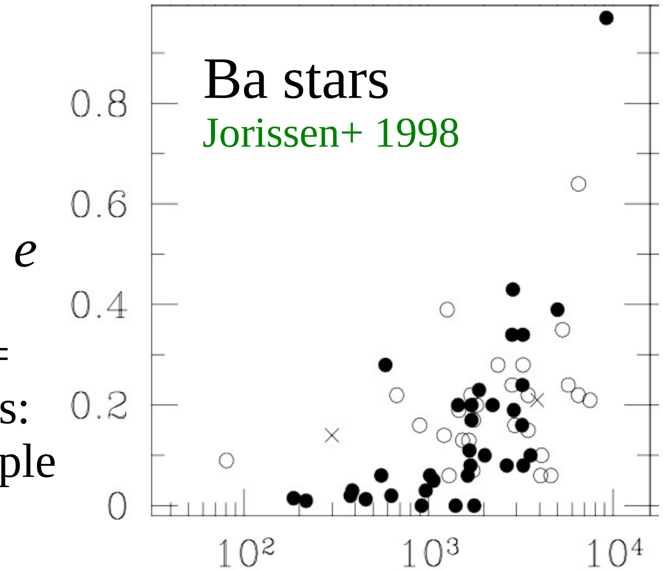


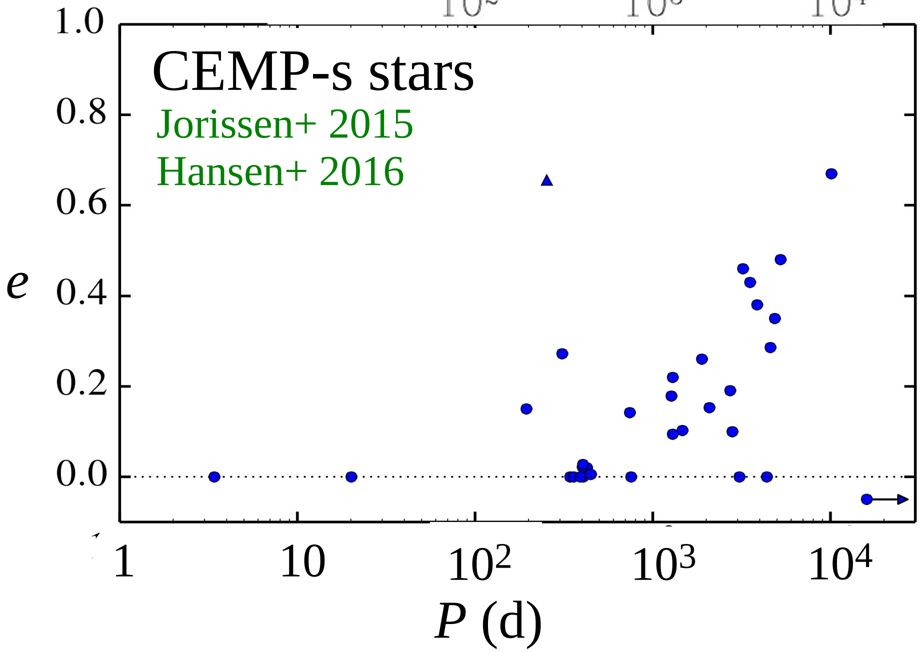
- high-precision RV monitoring of 22 CEMP-s stars over 8 yrs: Hansen+2016
  - 18 show orbital motion
  - 4 constant RV, apparently single
- scarcity of orbits with $P > 10^4$ d is *not* a selection effect Starkenburg+ 2014

orbits of polluted binaries

eccentricity versus orbital period

filled circles = strong Ba stars: complete sample





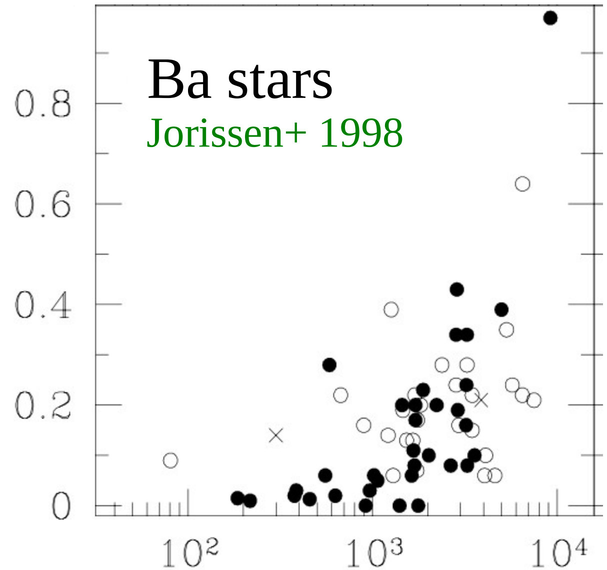
- periods mostly 10^2 – 10^4 days
- substantially eccentric (but less so than unevolved binaries at same *P*)
- mass functions consistent with WD companions
- very similar *e*-*P* distributions found among many classes of post-AGB/RGB binaries:
  - extrinsic S stars (without Tc)
  - post-AGB stars in binaries
  - S-type symbiotics
  - blue stragglers in old populations
  - sdB+MS binaries

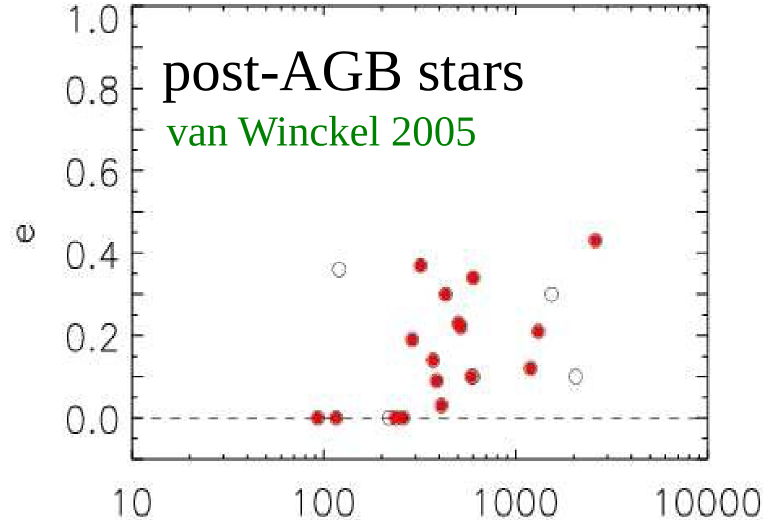
orbits of post-RGB/AGB binaries

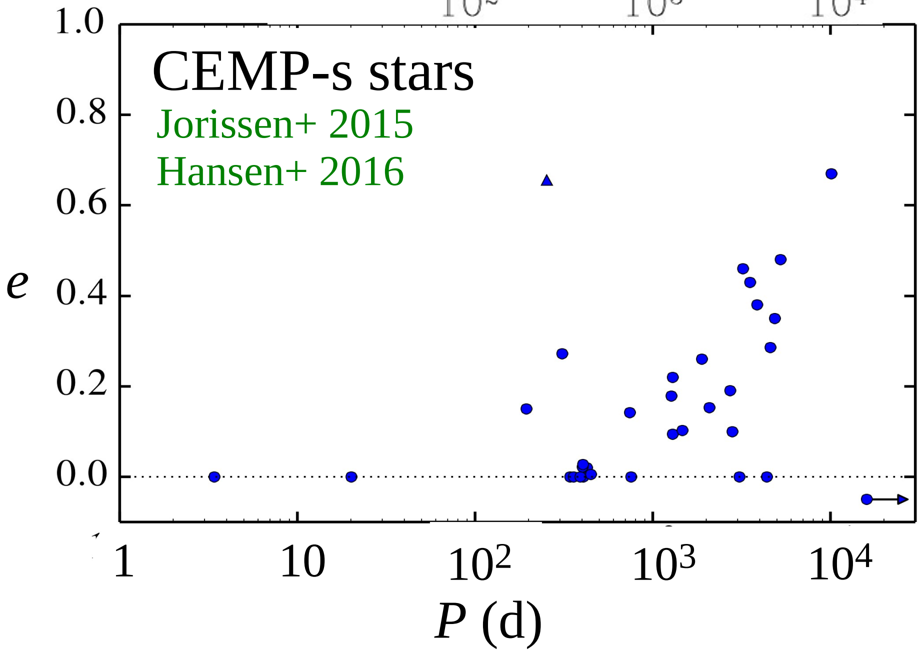
eccentricity versus orbital period

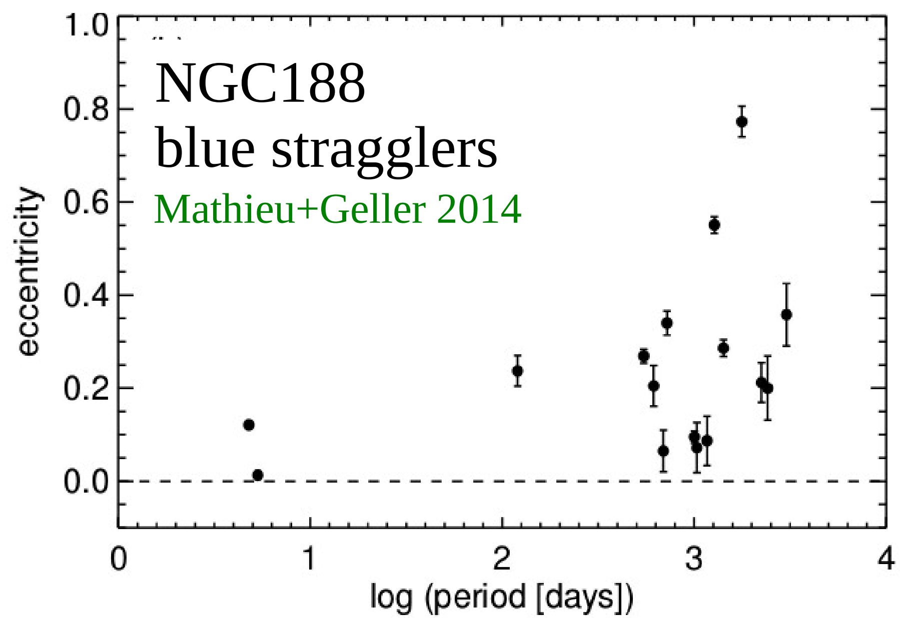
a common phenomenon!

filled circles = strong Ba stars: complete sample

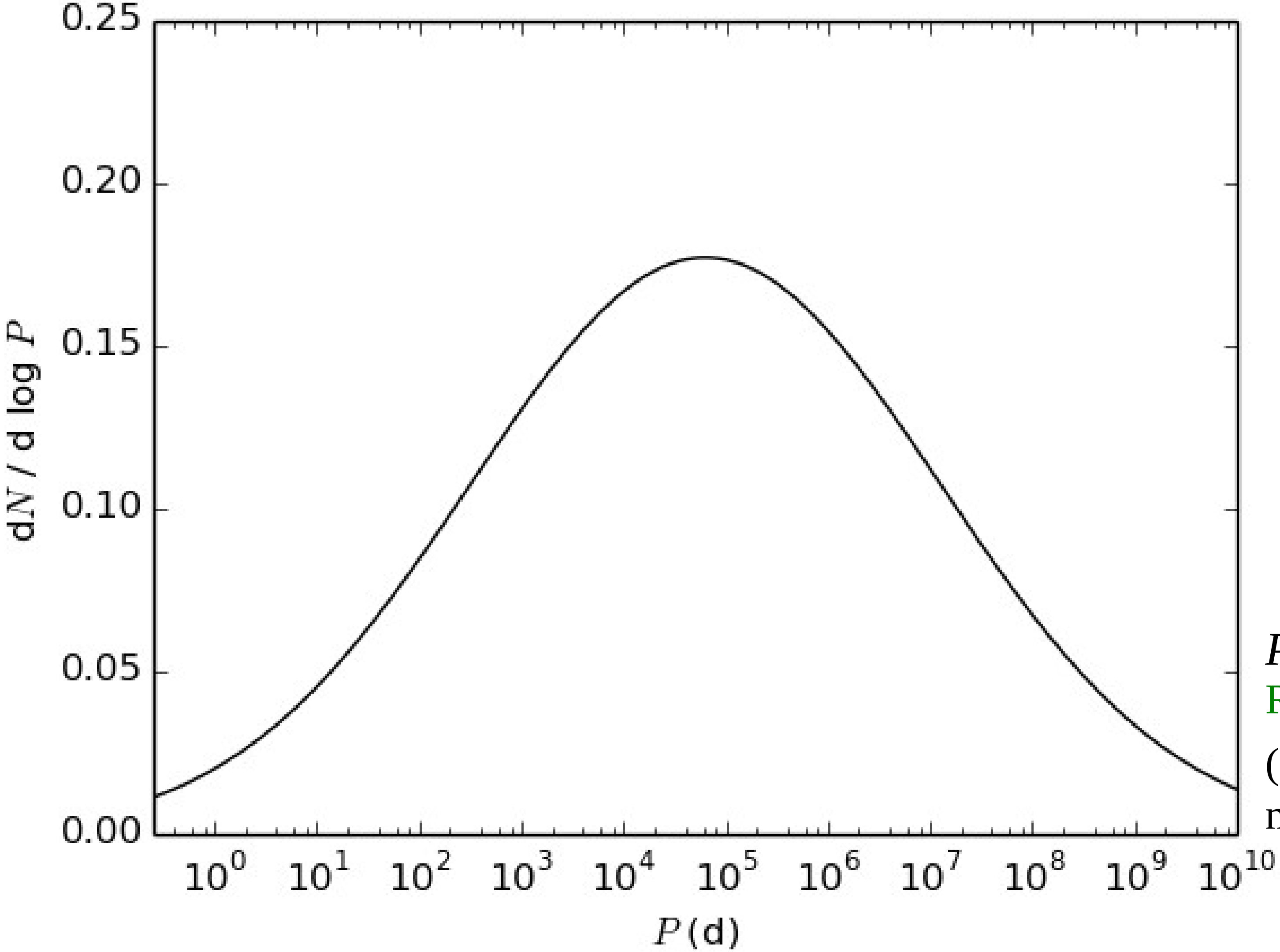








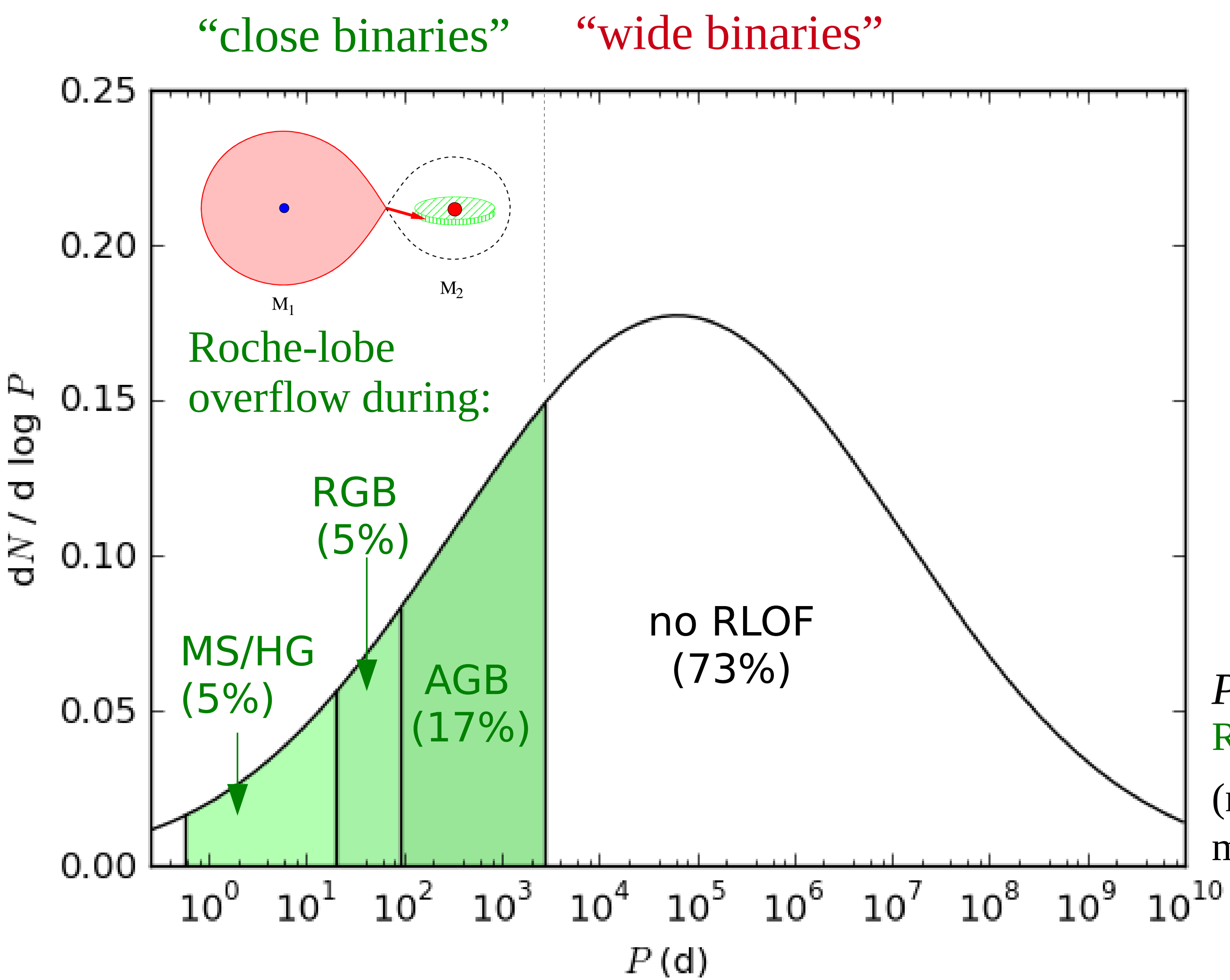
binary period distribution



P distribution for G dwarfs
Raghavan+2010

(may be flatter for more massive binaries)

binary period distribution

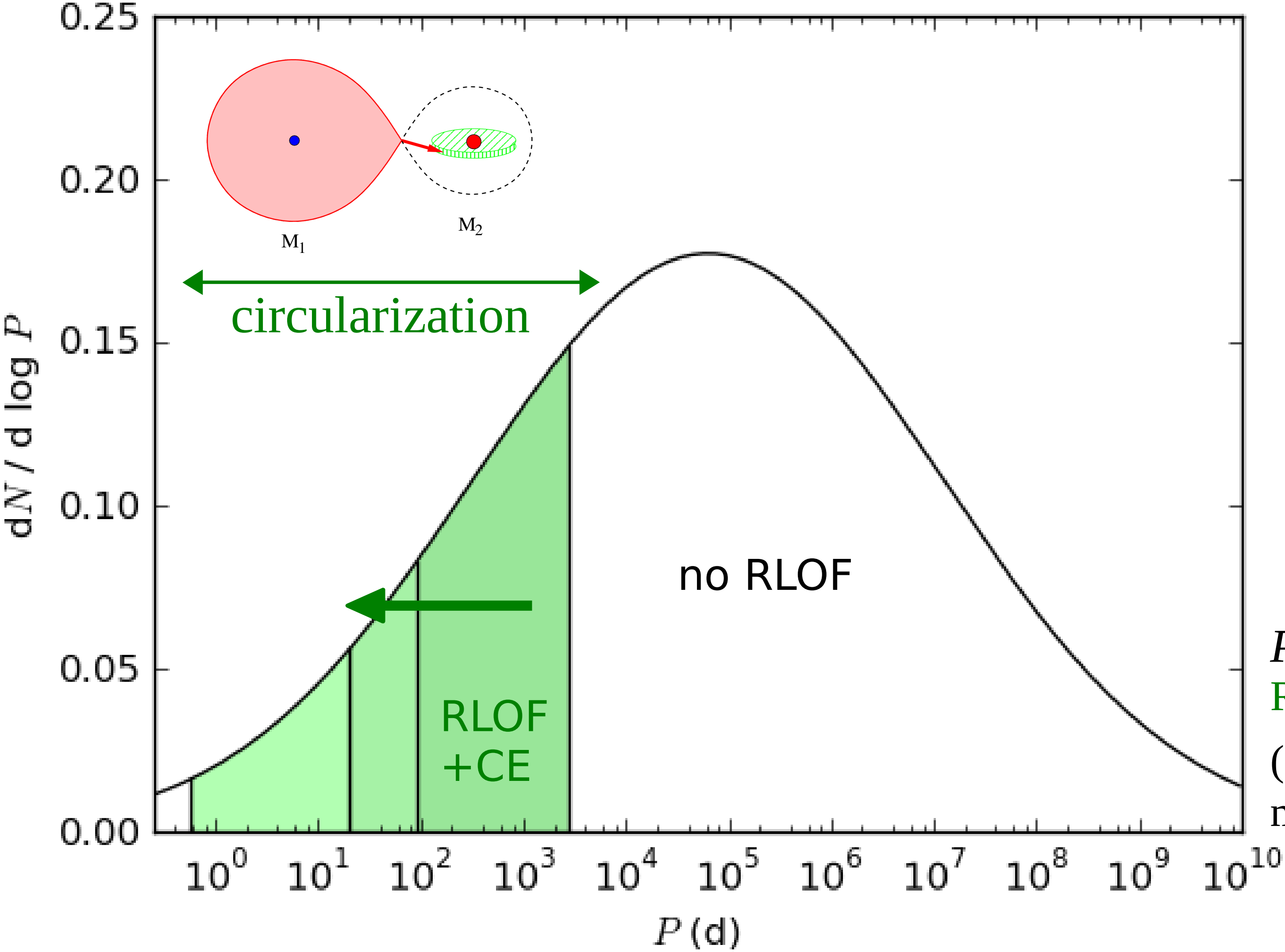


P distribution for G dwarfs
Raghavan+2010

(may be flatter for more massive binaries)

close binaries

- close binaries expected to circularize due to tidal interactions
- RLOF from red giants mostly unstable ⇒ expect spiral-in to closer orbits

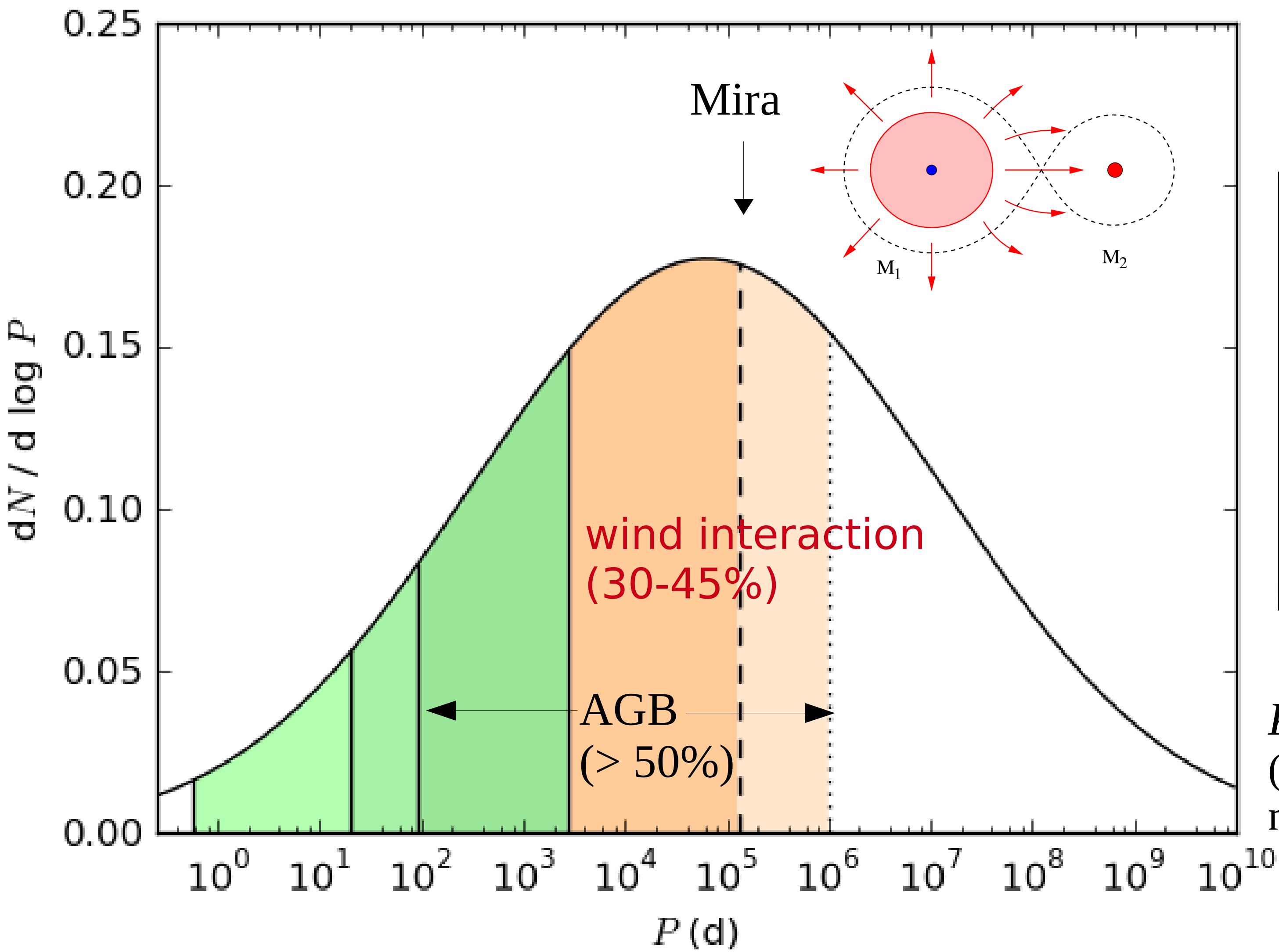


P distribution for G dwarfs
Raghavan+2010

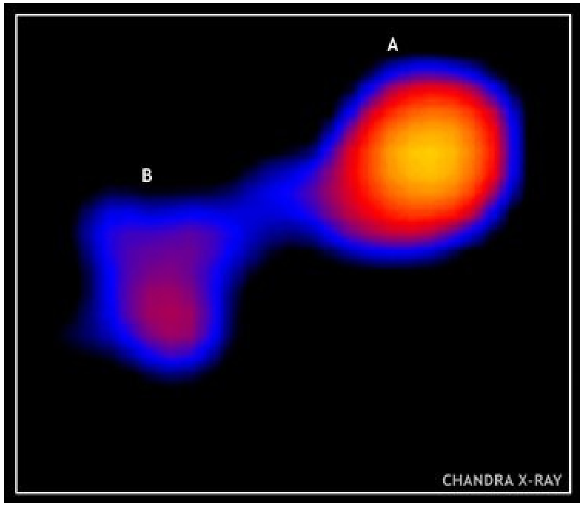
(may be flatter for more massive binaries)

wide binaries

- wide binaries interact by their stellar winds, especially on the AGB where the bulk of mass loss occurs (slow, dense winds)



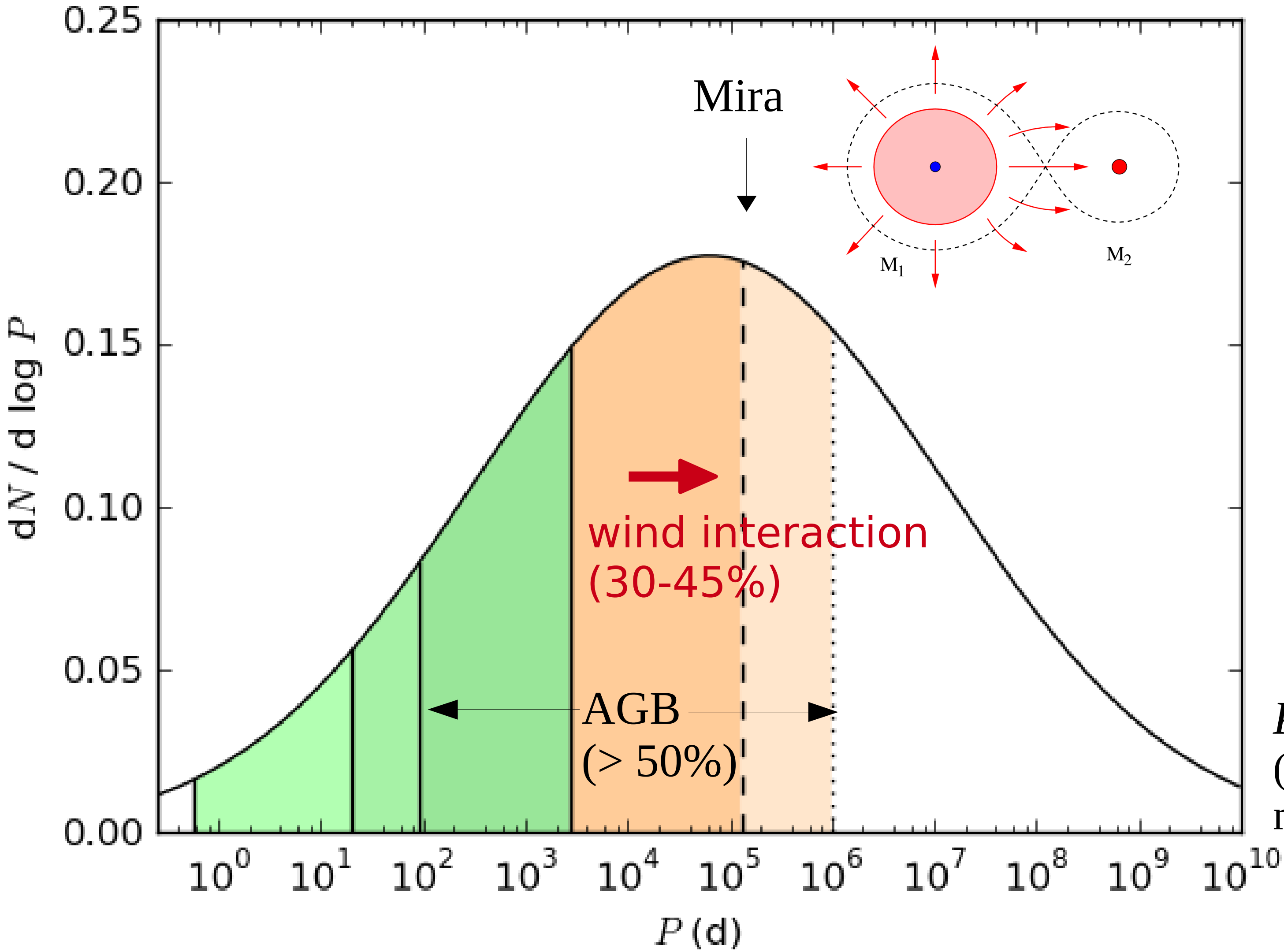
example: Mira AB, a wide symbiotic binary
Karovska+ 2005



P distribution for G dwarfs
(may be flatter for more massive binaries)

wide binaries

- wide binaries interact by their stellar winds, especially on the AGB where the bulk of mass loss occurs (slow, dense winds)



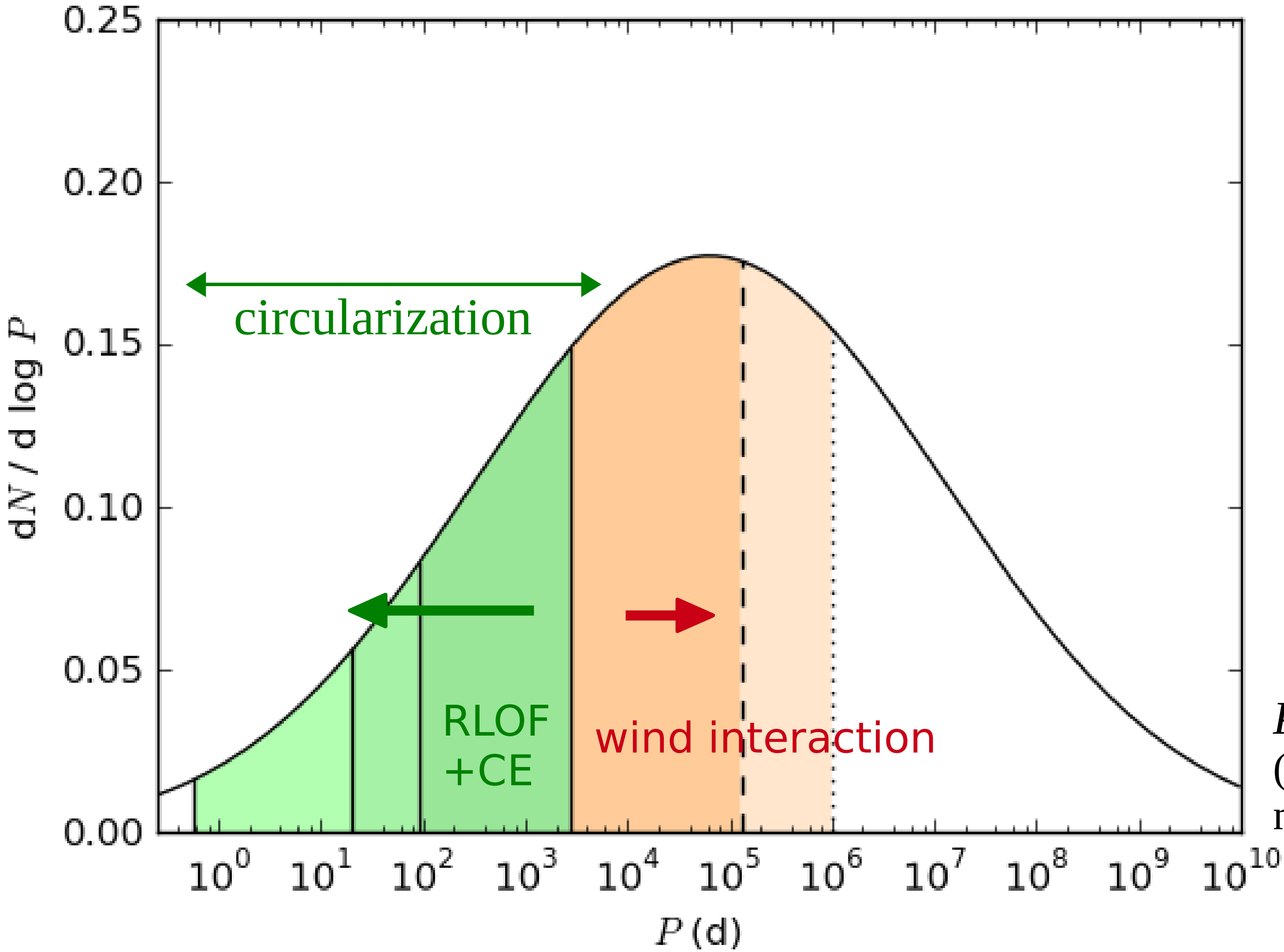
usually described as Bondi-Hoyle-Lyttleton flow:

- small fraction of wind is accreted
- if wind is roughly isotropic $\Rightarrow$ expansion of the orbit ($P \propto M_{\mathrm{tot}}^{-2}$)

P distribution for G dwarfs (may be flatter for more massive binaries)

descendants of AGB binaries

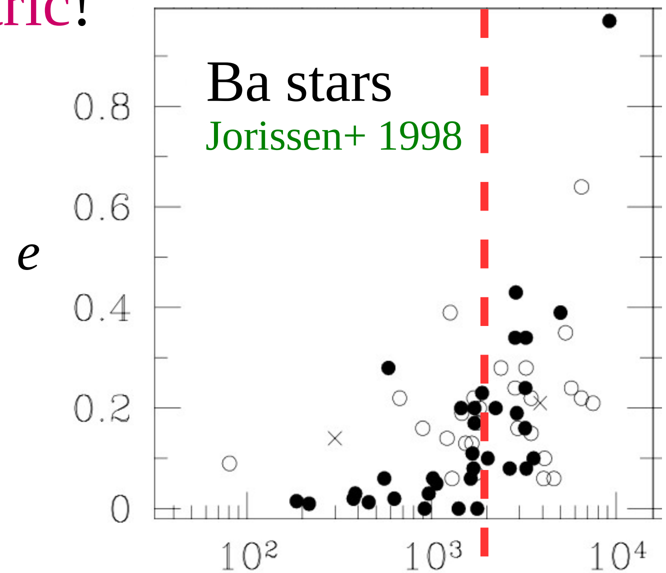
- expectations from binary evolution theory:
  close binaries will tighten and circularize, wide binaries will widen

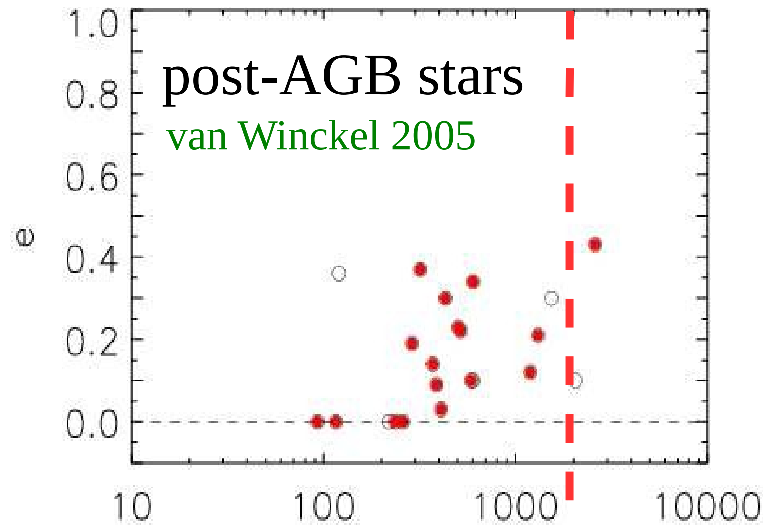


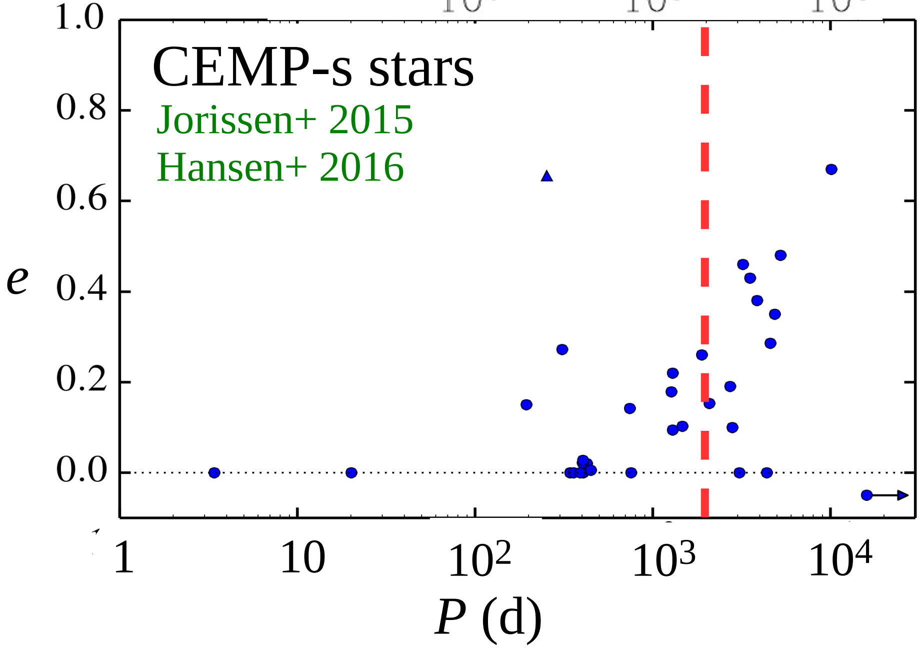
P distribution for G dwarfs
(may be flatter for more massive binaries)

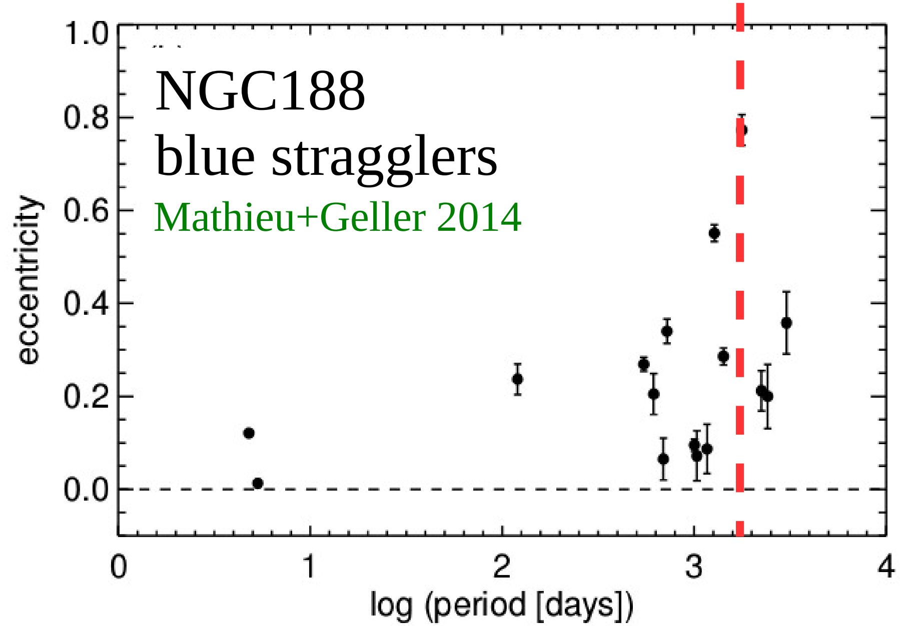
descendants of AGB binaries

- ... but known post-AGB binaries are right in the expected *P* gap, and often eccentric!



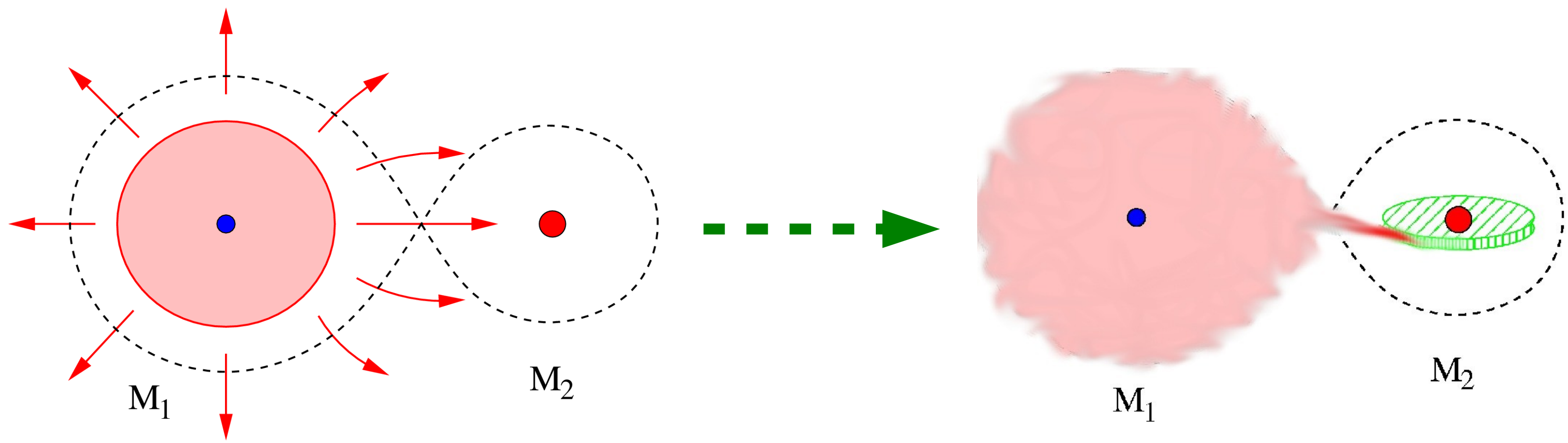






wind interaction revisited

- conditions for BHL accretion (isotropic outflow, $v_{\rm wind} \gg v_{\rm orb}$) do not hold for AGB binaries with slow, dense winds
- possibility of wind-RLOF: slow wind fills Roche lobe, highly distorted outflow
  Mohamed+Podsiadlowski 2007

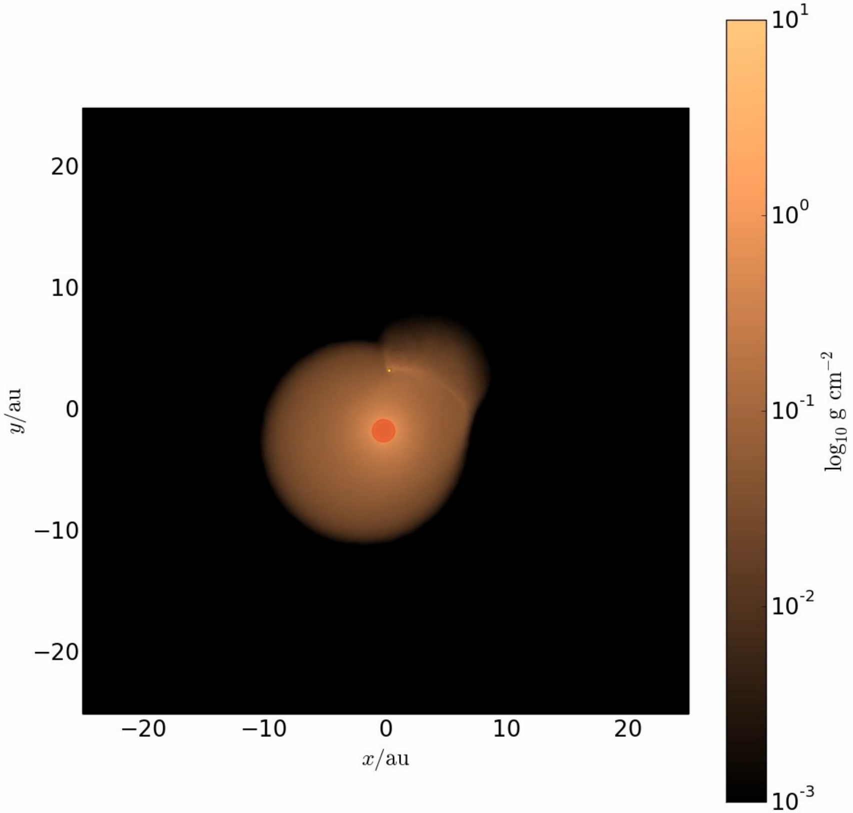


- confirmed by hydrodynamical simulations of AGB wind mass transfer
  e.g. Jahanara+ 2005, Mohamed 2010, Liu+ 2017, Chen+ 2017, Saladino+ 2017
  - larger accretion efficiencies
  - formation of circumbinary discs
  - enhanced angular momentum loss

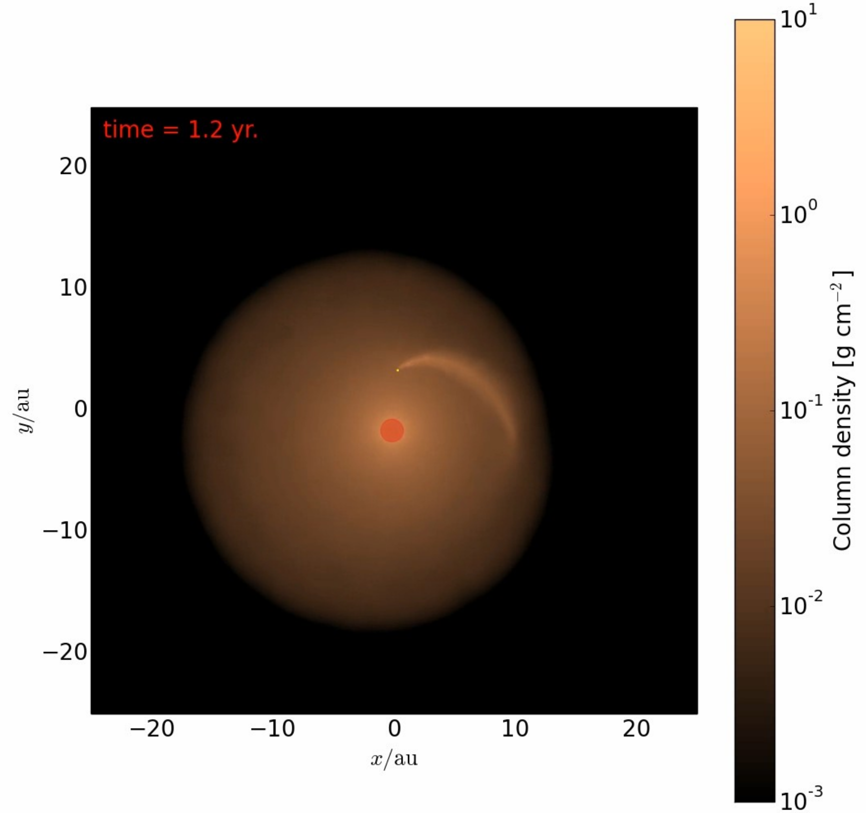
wind mass transfer simulations

- hydrodynamics (SPH) and orbital dynamics (N-body) coupled in AMUSE
  Saladino+ 2017, in prep.
- 3.0 (AGB) + 1.5 $M_{\rm sun}$ (sink) in circular orbit, $\mathrm{d}M_1/\mathrm{d}t = 10^{-6}\ M_{\rm sun}/\mathrm{yr}$, $a = 5$ AU

$v_{\rm w} = 15$ km/s ($\approx 0.5\ v_{\rm orb}$)

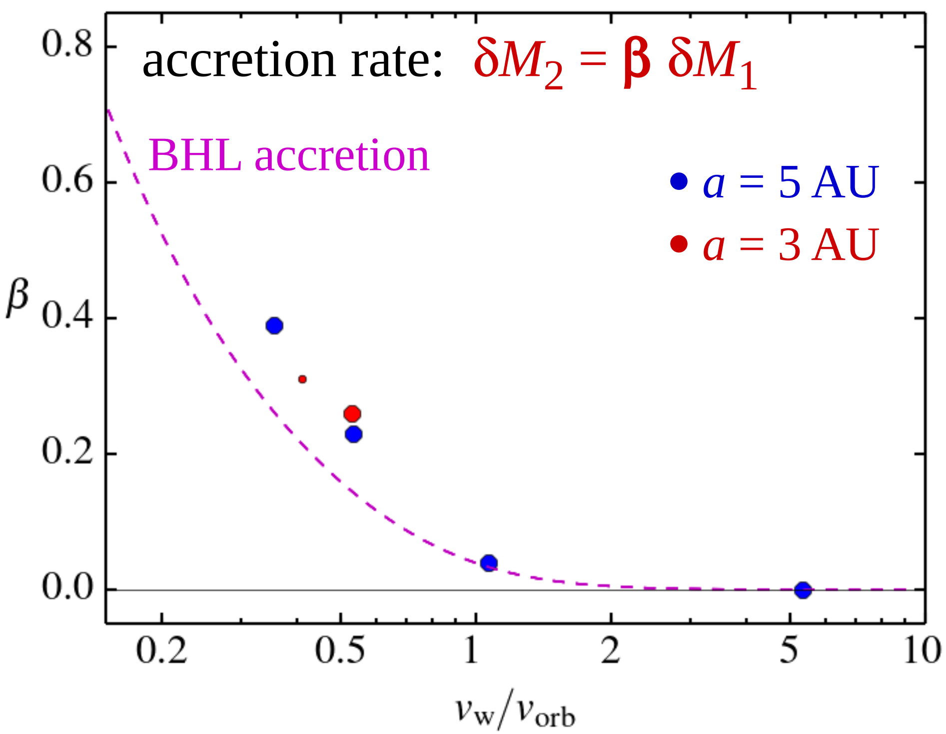


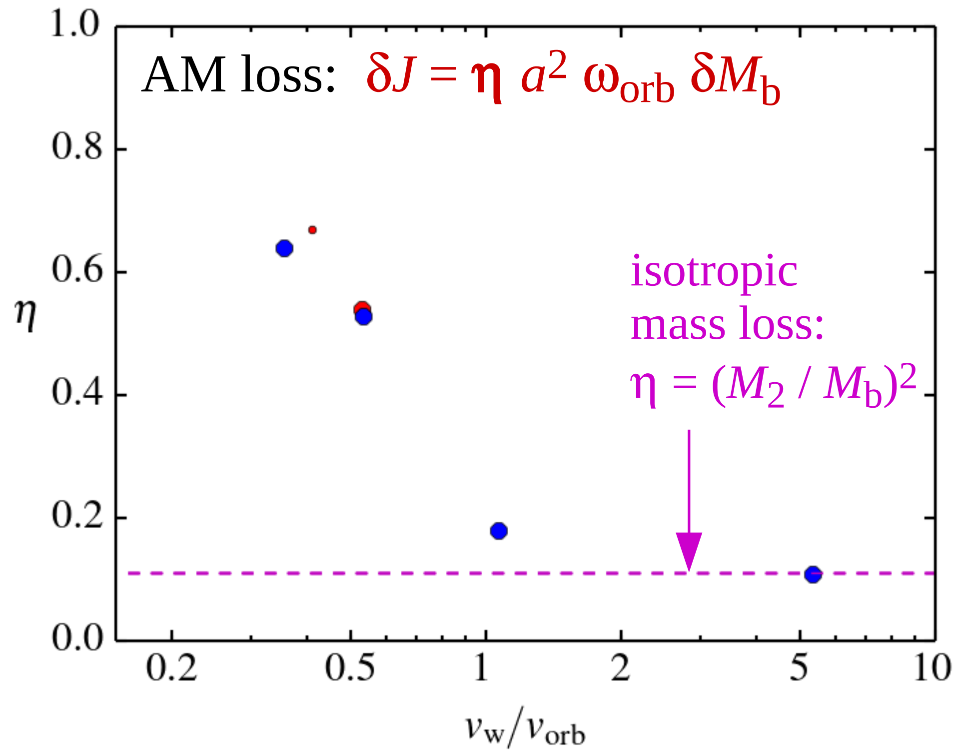
$v_{\rm w} = 30$ km/s ($\approx v_{\rm orb}$)



wind mass transfer simulations

- 3.0 (AGB) + 1.5 M_{sun} (sink) in circular orbit, $dM_1/dt = 10^{-6}\ M_{sun}/yr$
- measure accretion rate and angular momentum loss as function of v_{wind} and a:
  Saladino+ 2017, in prep. (cf. also Chen+ 2017)
  - $v_w > v_{orb}$: accretion ~ BHL, nearly isotropic outflow: orbit expands
  - $v_w < v_{orb}$: accretion > BHL (up to 40% of wind), strongly modified outflow: *orbit shrinks* as result of enhanced AM loss

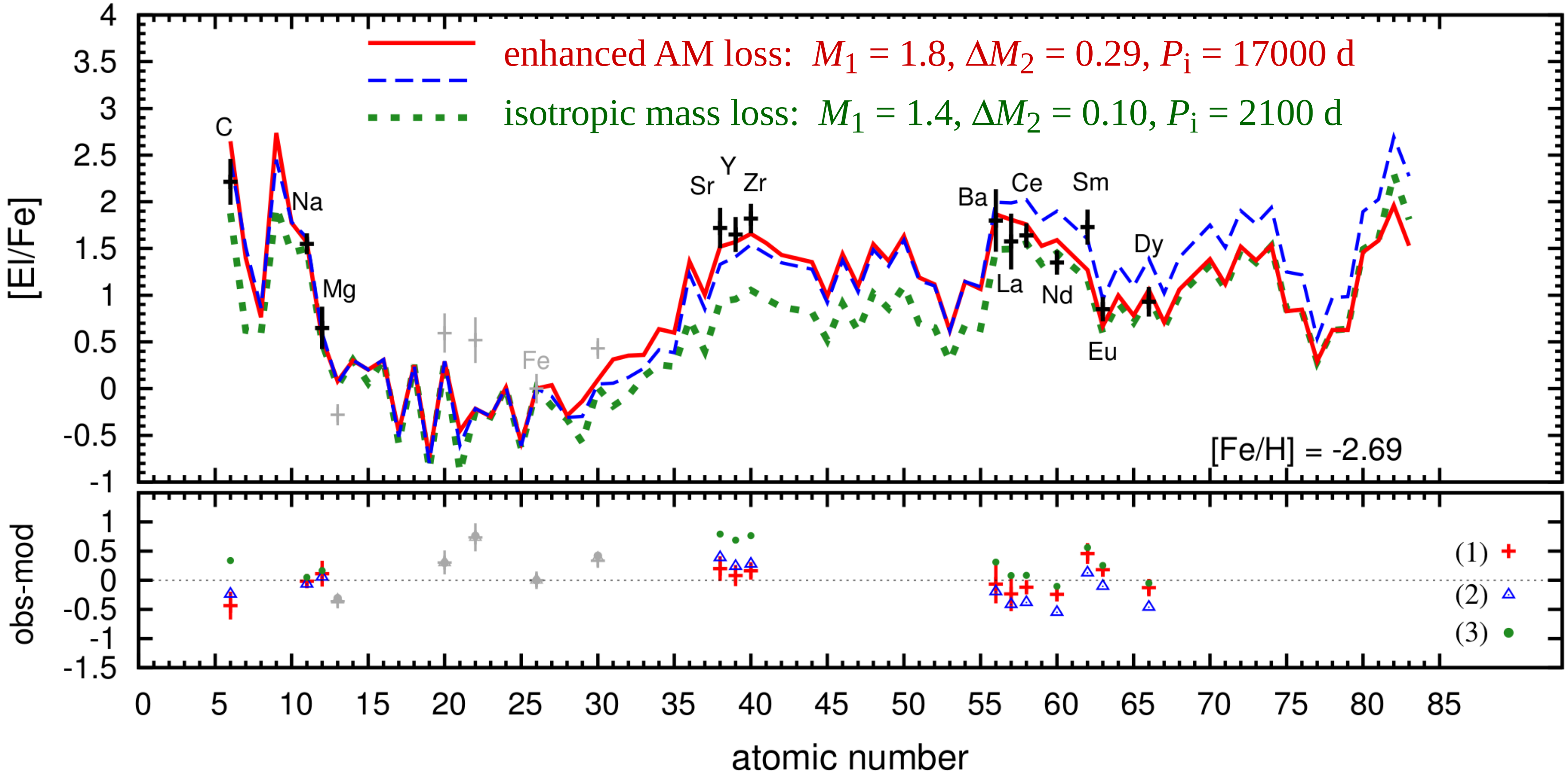




modelling CEMP-s binaries

- Abate+ 2015: model 14 CEMP-s binaries with orbits known at the time
  - fit measured abundances, surface gravity **and** orbital period
  - find best-fitting binary model, using recent AGB nucleosynthesis models
    Karakas+2010, Lugaro+2012

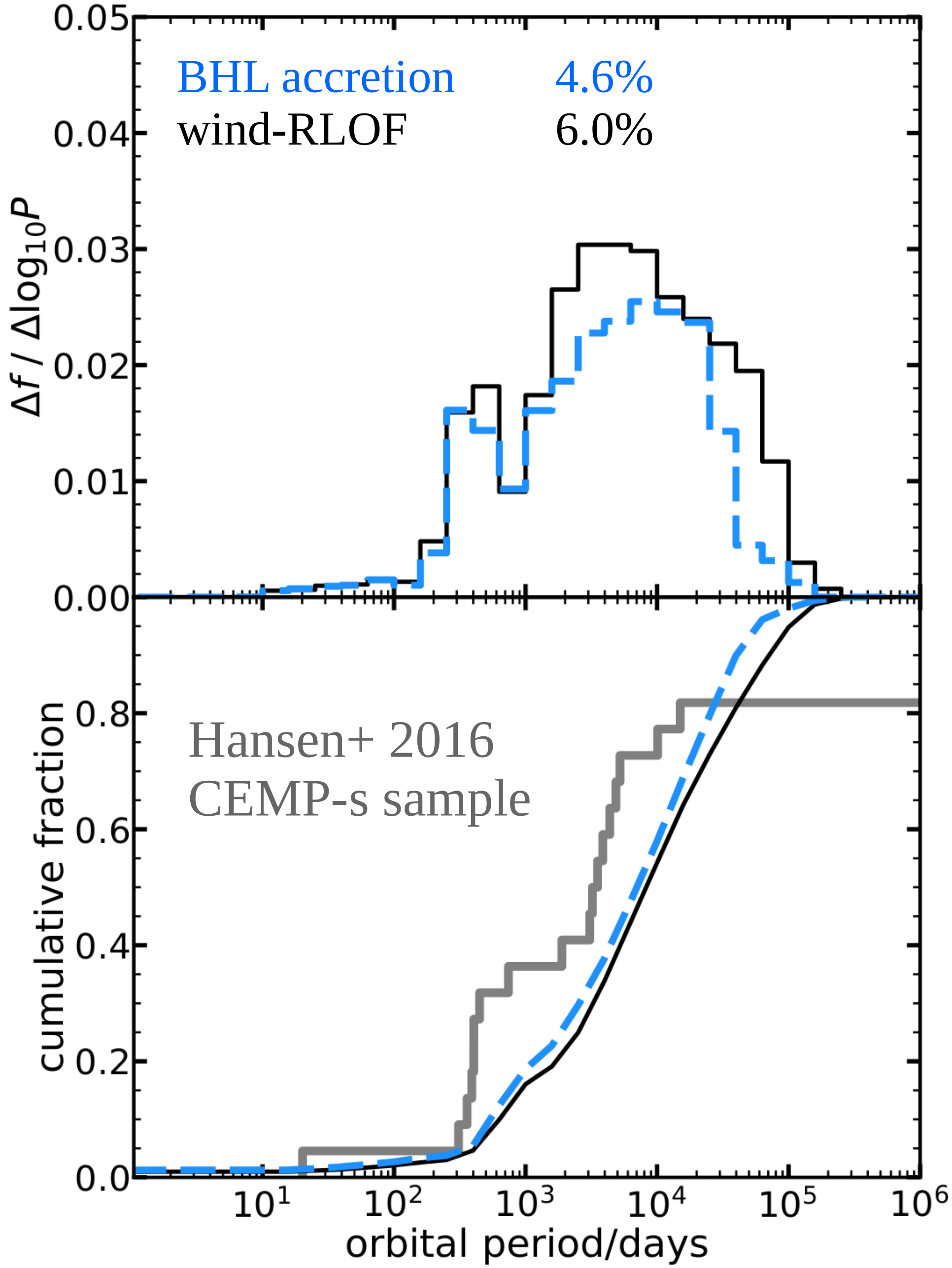
example: CS22942–019, P = 2800 d



modelling CEMP-s binaries

- Abate+ 2015: model 14 CEMP-s binaries with orbits known at the time
  - fit measured abundances, surface gravity **and** orbital period
  - find best-fitting binary model, using recent AGB nucleosynthesis models
    Karakas+2010, Lugaro+2012
- generally good fit to CEMP-s abundance patterns (but *not* the CEMP-r/s)
- in many systems: large amount of accretion (~0.3 M_{sun}) needed to reproduce observed abundances
  - N.B. accreted material is diluted by *thermohaline mixing*
    Stancliffe+2007, Stancliffe+Glebbeek 2008
- this requires efficient accretion in close orbits and enhanced AM loss (~2 × J_{tot}/M_{tot}) during wind accretion to match P_{orb}

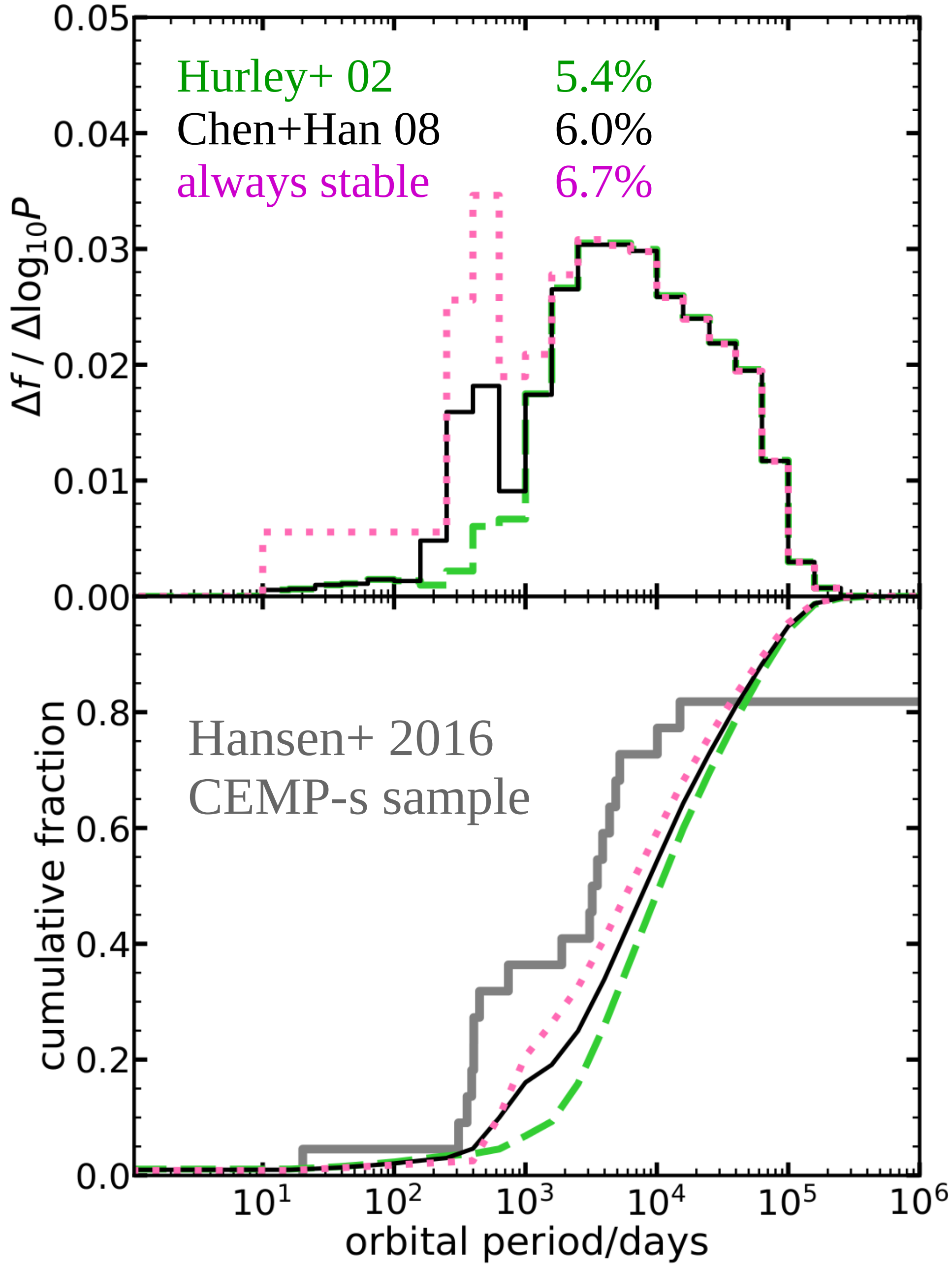
CEMP-s population synthesis



binary population synthesis of CEMP-s stars: Abate+ 2015, 2017

- solar neighbourhood IMF and binary statistics
- can (just) reproduce observed CEMP-s fraction of ≈ 6% at [Fe/H] > –2.5 (SDSS/SEGUE, Lee+2014)
- mostly resulting from wind mass transfer, which needs to be efficient (wind-RLOF)
- requires wide range of initial orbits ($P \sim 10^3 - 10^{5.5}$ d)
- isotropic wind assumption ⇒ final periods are too wide

CEMP-s population synthesis



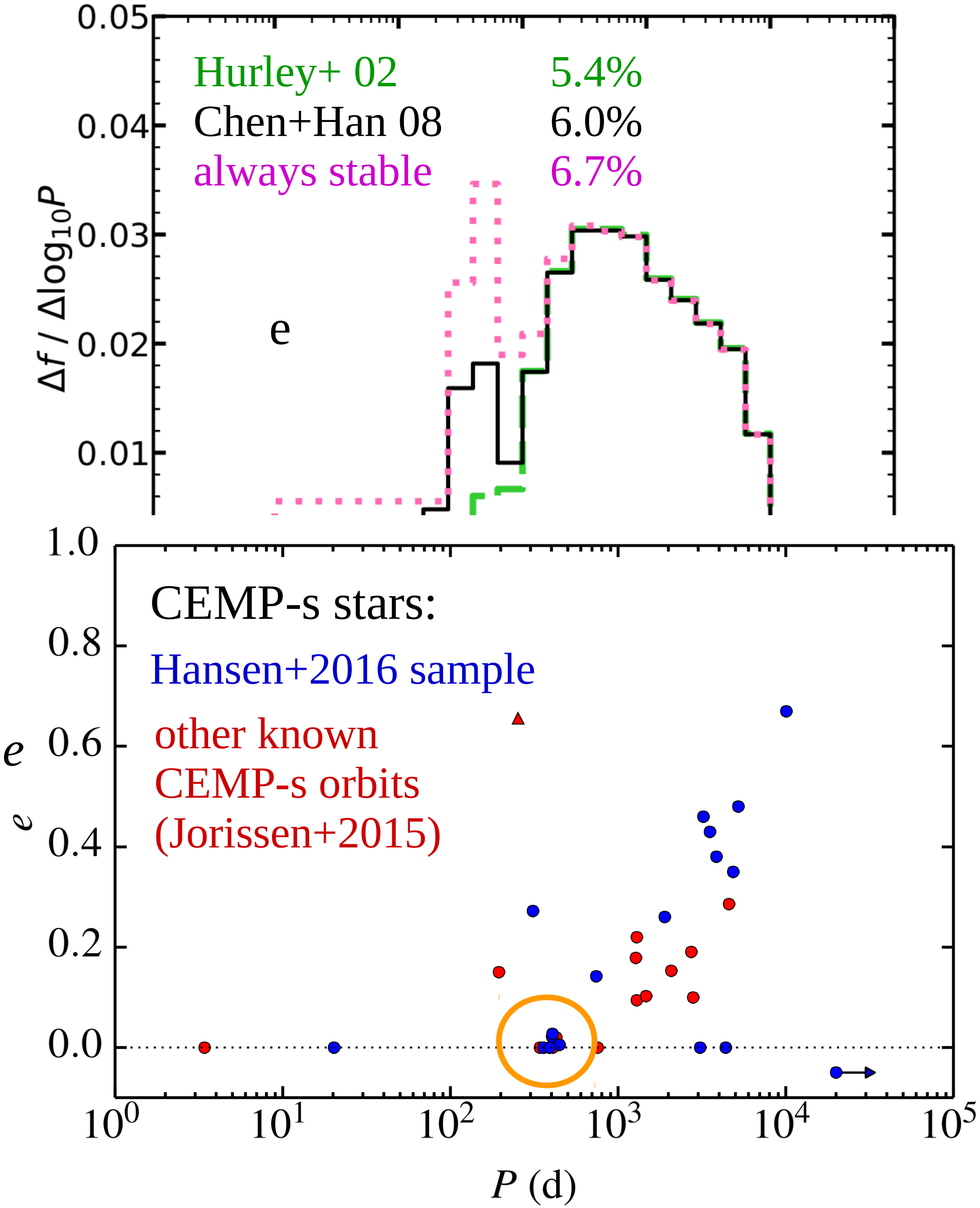
contribution from stable RLOF?
Abate+2017, in prep.

- RLOF from red giant can be *stable* if initial mass ratio $M_1/M_2 \sim 1$
  Chen+Han 2008, Woods+ 2011, Pavlovskii+Ivanova 2014

  $\Rightarrow$ modest effect on overall P distribution

- may explain circular CEMP-s orbits with $P \sim 400$ d?

CEMP-s population synthesis



contribution from stable RLOF?

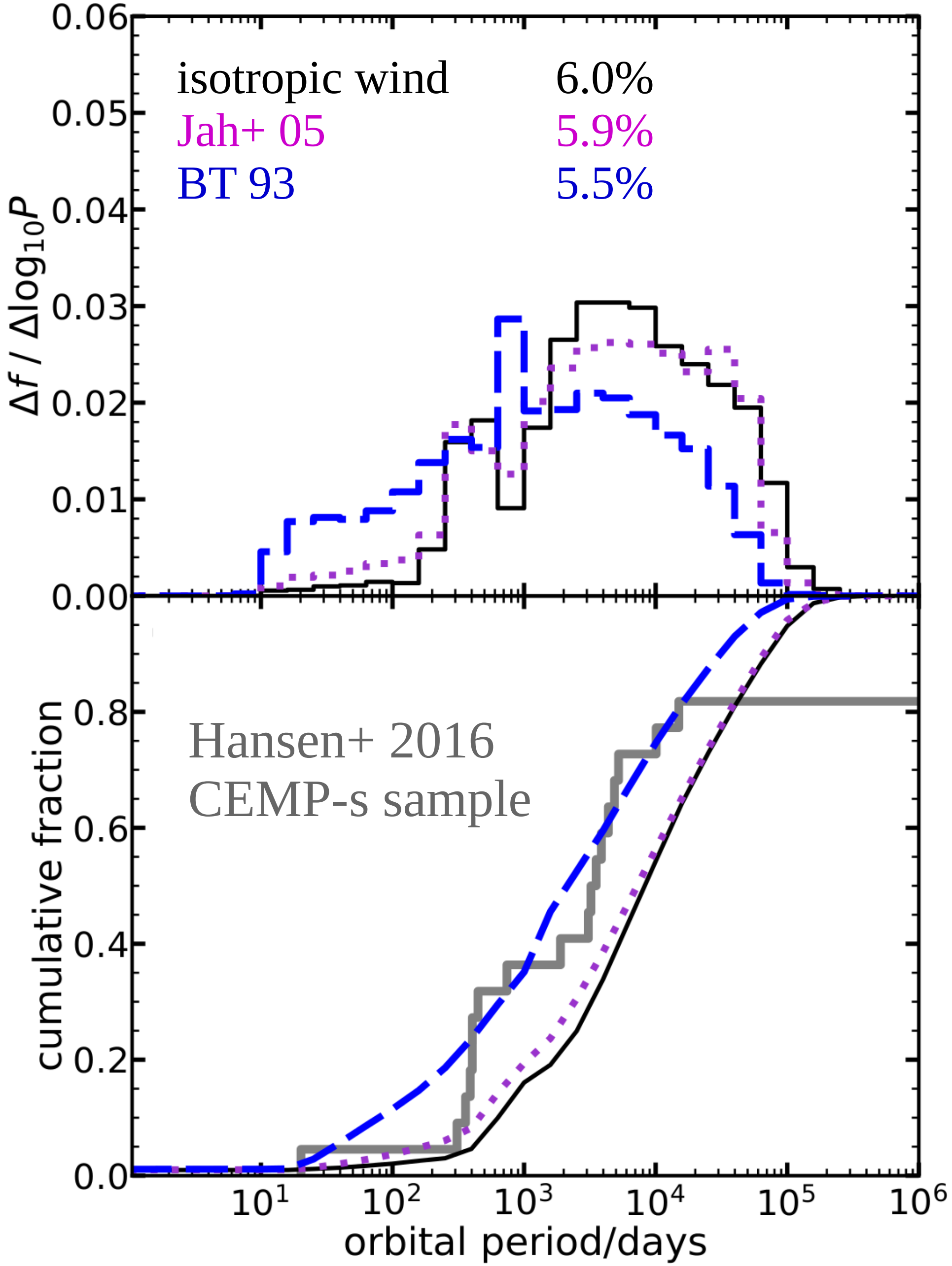
Abate+2017, in prep.

- RLOF from red giant can be *stable* if initial mass ratio $M_1/M_2 \sim 1$
  Chen+Han 2008, Woods+ 2011, Pavlovskii+Ivanova 2014

  ⇒ modest effect on overall P distribution

- may explain circular CEMP-s orbits with $P \sim 400$ d?

CEMP-s population synthesis



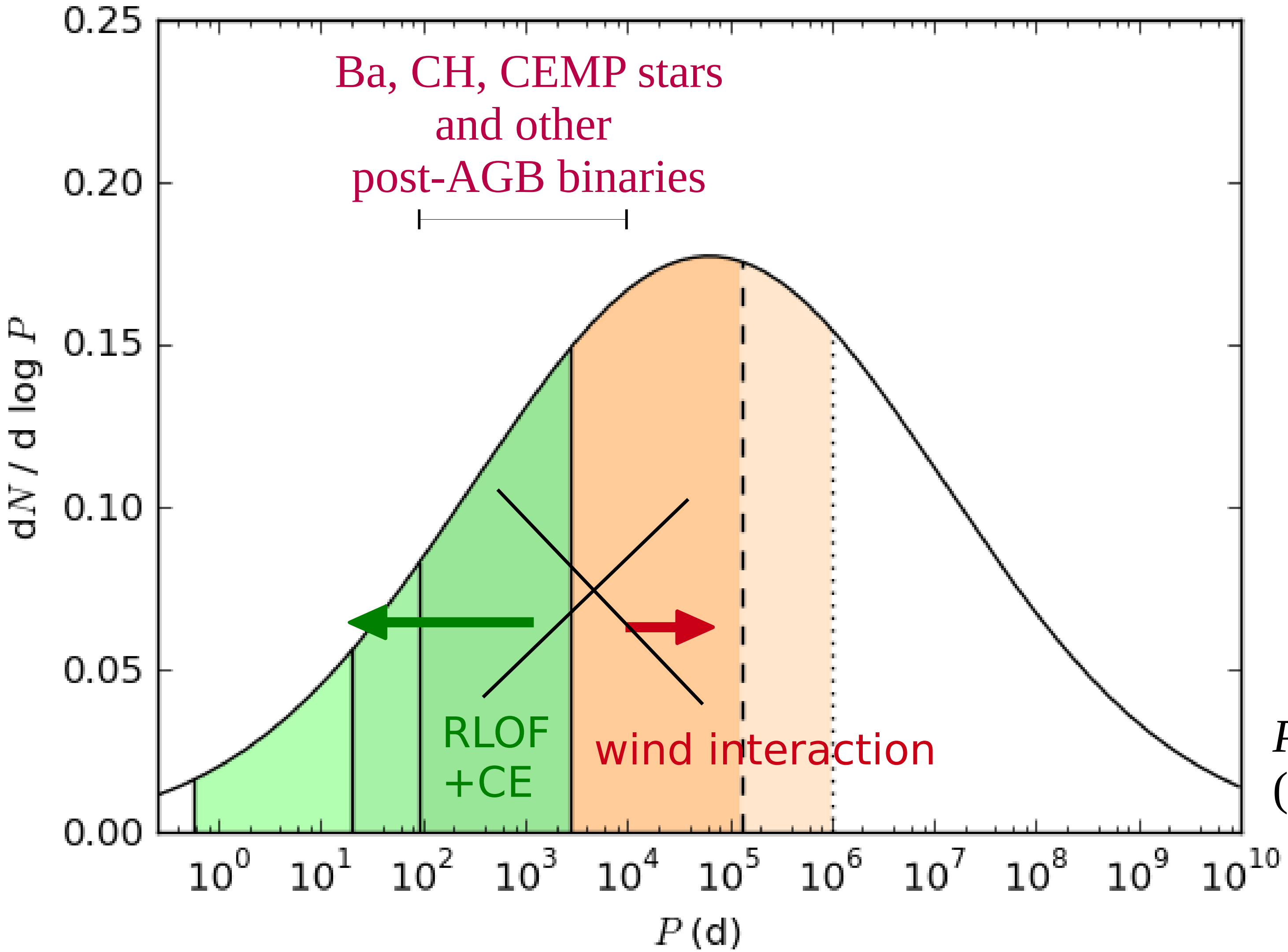
enhanced angular momentum loss?
Abate+2017, in prep.

- parameterized AM loss, compared to isotropic wind:
  - hydro models of wind transfer
    Jahanara+2005
  - ballistic "wind" simulations
    Brookshaw+Tavani 1993
    (probably overestimates AM loss)

⇒ strong orbital AM loss helps producing close CEMP-s orbits

descendants of AGB binaries

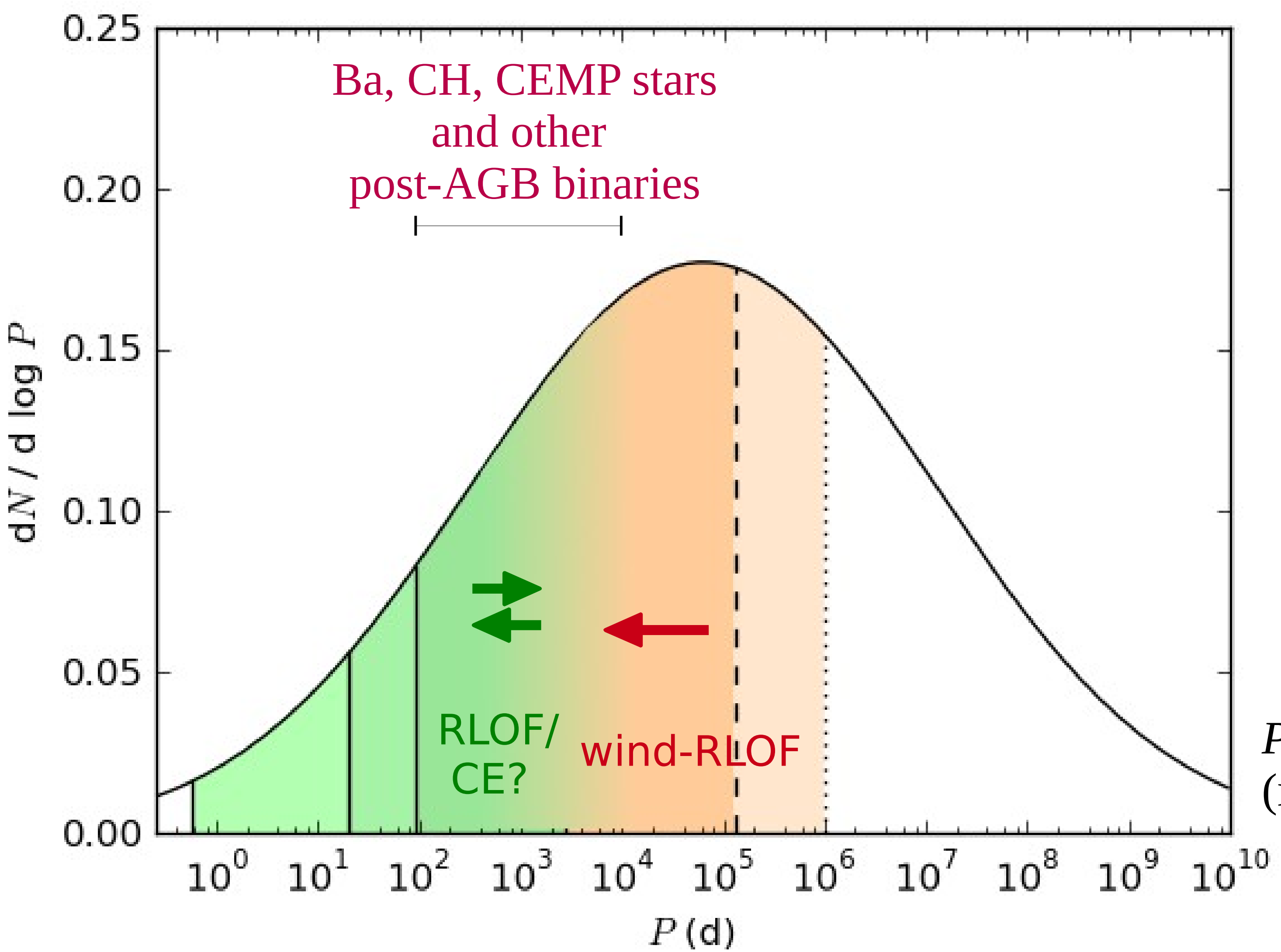
- observational evidence: a continuity of orbital properties across close/wide-binary boundary



P distribution for G dwarfs (may be flatter for IM stars)

descendants of AGB binaries

- observational evidence: a continuity of orbital properties across close/wide-binary boundary



P distribution for G dwarfs (may be flatter for IM stars)

summary

- >50% of low- and intermediate-mass binaries undergo their main interaction during the AGB phase
  - produces variety of (chemically polluted) binaries with very similar orbital properties
  - provides interesting tests of both AGB nucleosynthesis and (still poorly understood) binary interaction processes
- evidence from both hydro simulations and modelling CEMP-s binaries:
  - efficient wind accretion (wind-RLOF)
  - orbital shrinkage during AGB wind interaction
  - pumping of eccentricity during interaction, process still unclear